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Magnetic Moments of Composite Fermions*

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Once upon a time physicists believed that nucleons and pions were elementary like electrons and photons, and that Yukawa's theory of nuclear forces was the analog of QED for strong interactions. Then the Δ was discovered, and then the ρ and other pion resonances, and it became apparent that neither the pion nor the nucleon was elementary and that both had a composite structure. Pions and nucleons now seem to be very similar objects, instead of being very different like the electron and photon, and made of the same basic building blocks: spin 1/2 quarks bound by colored gluons. But perhaps history will repeat itself. Maybe 25 years from now a lecture at Orbis Scientiae will begin with the statement "Once upon a time physicists believed that quarks and gluons were elementary, and that Quantum Chromodynamics (QCD) was the analog of QED for strong interactions. Then ...?"

Today we have the new QXD model for everything, where X = A, B, C, D, E, F, G, etc. So far there are only models for X = C, E, F and G, but no doubt the others will eventually be discovered as well. However, it is amusing that in the great excitement about non-Abelian gauge theory, the original non-Abelian gauge model for hadron dynamics has faded away. This was the gauge theory of strong interactions mediated by the octet of vector mesons ρ, ω and K^* coupled to conserved vector currents.

The SU(3) group of unitary symmetry was originally introduced by Gell-Mann and Ne'eman to describe an SU(2) x U(1) classification for two completely different types of particles, strange and nonstrange, which seemed to belong together in common multiplets. This SU(2) x U(1) of isospin and strangeness motivated a search for a higher symmetry to unify the two. The SU(3) gauge theory called the Eightfold Way brought strange and nonstrange particles into unified multiplets and was believed to be the non-Abelian gauge theory of the world. Today it is called flavor and dismissed as an irrelevant complication in the QCD description of strong interactions. The unification of strange and nonstrange particles into flavor SU(3) remains, but it is no longer a candidate for a gauge theory. The ρ, ω and K^* are not gauge bosons but composite objects and flavor SU(3) has been revealed to be an accidental symmetry based upon our incomplete knowledge of the number of flavors. The basis for the SU(n) flavor classification is found in a composite model for hadrons from n fundamental building blocks.

Today we again have an SU(2) x U(1) classification for two completely different types of particles quarks and leptons, which seem to belong together in common multiplets. Again there is a search for a new higher symmetry to unify the two and be the non-Abelian gauge theory of the World. The main candidates for unification of quarks and leptons are SU(5) and higher groups containing SU(5). But there is again the alternative approach that attributes these classifications to a composite model with new basic building blocks, and not to a fundamental gauge theory.

Some suggestions already are appearing that quarks and leptons are not elementary but made of more fundamental objects called rishons or preons.[1] The name rishon comes from a Hebrew word with several interpretations. It is also a short form for the name of a town between Tel Aviv and Rehovot, famous for its winery. A standard excursion for tourists staying in Tel Aviv includes a trip to Rehovot to visit the Weizmann Institute with a stop at Rishon. My friends in public relations at the institute used to complain about the difficulty of explaining anything to these tourists after they had imbibed freely at the winery. I like to think of rishon physics as the kind of physics done under the influence of Rishon.

The rishon model is described by the cube shown in Fig. 1, with the positron, u quark, $\bar{d}$ antiquark and neutrino at the corners. If the cube is taken to be the unit cube, with the neutrino corner at the origin, then the coordinates of each vertex have the form (x,y,z) where x, y and z can be either 0 or 1. If we denote the value 0 by V and the value 1 by T, the coordinates of each vertex are labeled by the constituents of the particle at that vertex in the rishon model. The electric charge axis runs along the diagonal of the cube between the (V,V,V) and (T,T,T) vertices, and color SU(3) multiplets appear on the planes perpendiclar to this diagonal. The values of the electric charge are (0, 1/3, 2/3, 1) for the particles at the vertices of the cube.

Those who perfer integral charges can choose a different charge axis to obtain the Han-Nambu cube, shown in Fig. 2. Here the charge is the z-axis, and the particles have either charge 0 or +1, with the average charge of each color triplet being the conventional fractional charge of 1/3 or 2/3. Here there are no rishons. It is interesting that the difference between the integrally charged and fractionally charged models has a simple geometrical representation, a rotation of the charge axis in the cube.

One can ask whether the T and V rishons are really the fundamental constituents of quarks and leptons, or whether the geometric picture is more fundamental and somehow related to grand unified gauge theories. One can even speculate that the cube is part of the lattice used in lattice gauge theories, and somehow related to properties of space-time. If leptons are a fourth color, then 3+1 colors may be related to 3+1 dimensional space. But we do not indulge in further speculations here.

The contest between symmetries and quark models as the fundamental description of hadron structure was resolved in favor of the composite model by the experimental data. We therefore look in the experimental data to find the clues to choose between symmetry and composite descriptions of the structure of quarks and leptons.

Magnetic moments may provide such clues, since anomalous magnetic moments are clear evidence for composite structure. There are two kinds of structure with very different properties, dynamic and static.

1. Dynamic structure was the original hypothesis to explain the anomalous magnetic moment of the nucleon. In the model of a bare nucleon with a Dirac moment and a meson cloud, the anomalous moment arises from electromagnetic currents produced by the emission and absorption of bosons or fermion pairs.

2. Static structure explains the magnetic moments of atoms, and also describes the nucleon magnetic moments in the constituent quark model. Here the angular momenta and the magnetic moments of the constituents are static properties of the bound state and add vectorially to give the total angular momentum and the total magnetic moment. The Dirac moment of such a static composite state has no simple physical meaning.

The present status of particle magnetic moments is summarized as follows:

1. Nucleon moments are well described by a static quark model at the 2% level.
2. The Λ moment is well described by the static quark model with SU(3) symmetry breaking at the 2% level.
3. The new experimental values of the Σ and Ξ moments are in disagreement with the static quark model at the 20% level.
4. Lepton moments are described extremely well by Dirac theory, suggesting that they are elementary point particles. Any composite model must avoid effects of structure which destroy the g-2 predictions.

The successful SU(6) prediction for the nucleon moments,

$$\left(\frac{\mu_p}{\mu_n}\right) = -\frac{3}{2} \quad , \tag{1}$$

began a revolutionary development in our understanding of hadron structure. The old dynamical model predicted that

$$\mu = \mu_{Dirac} + \mu_{Atom}(g) \quad , \tag{2}$$

where the anomalous moment depended on the strong interaction coupling constant g. Nobody noticed that the experimental moments satisfied (1) because only the anomalous moments were expected to be related. There was no reason for the total moment to be simple! The SU(6) prediction (1) came as a great mystery.

Now we have a static quark model which gives simple predictions for total moments.[2] And there are new measurements of μ_Λ, μ_{Ξ^0}, and μ_{Ξ^-}. The value of μ_Λ agrees with two quark model predictions with fantastic precision.[4,5] But there are serious difficulties with μ_{Ξ^0}, μ_{Ξ^-} and μ_{Σ^+}, which do not fit any model.[3,6,7] Better measurements of μ_{Σ^-} are needed. A detailed discussion of these difficulties is presented elsewhere.[8]

Baryon magnetic moments are calculated from a static SU(6) wave function for three quarks with Dirac moments. This gives two predictions for μ_Λ which depend on the strange and nonstrange quark masses m_s and m_u.

$$\mu_\Lambda = -\frac{1}{3}\left[\frac{1}{\mu_p} + \frac{m_s - m_u}{m_p}\right]^{-1} , \tag{3a}$$

$$\mu_\Lambda = -\frac{\mu_p}{3} \times \frac{m_u}{m_s} . \tag{3b}$$

Both of these predictions reduce to the SU(6) symmetry prediction $\mu_\Lambda = -\mu_p/3$ in the SU(3) symmetry limit $m_s = m_u$.

Two independent estimates of SU(3) symmetry breaking have been proposed using experimental hadron masses. If we set

$$m_s - m_u = M_\Lambda - M_p , \tag{4a}$$

in Eq. (3a) we obtain[5] $\mu_\Lambda = -0.61$. If we set

$$\frac{m_u}{m_s} = \frac{m_{\Sigma*} - m_\Sigma}{m_\Delta - m_N} . \tag{4b}$$

In Eq. (3b) we obtain[4] $\mu_\Lambda = -0.61$ again.

Both predictions (3-4) are in remarkable agreement with the new experimental value $\mu_\Lambda = -0.6138 \pm 0.0047$ n.m.

Why does this work so well? Why is $m_s - m_u$ given by $M_\Lambda - M_p$ and not $M_{\Sigma*} - M_\Delta$?

The answer to this question is given in the post card shown in Fig. 3, sent by Andrei Sakharov from his exile in Gorkii. It appears in an old 1966 paper[9] and comes from a naive static constituent quark model which has had surprising success. The model obtains a universal formula for the flavor and spin dependence of the mass M of any hadron from the assumption that all flavor and spin dependence comes from the flavor dependence of the quark mass m and from a two-body hyperfine interaction with a spin dependence $\vec{\sigma}_i \cdot \vec{\sigma}_j$ and a flavor dependent coefficient f_{ij},

$$M = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{f_{ij}} \langle v_{ij} \rangle$$

$$+ \text{ terms independent of spin and flavor} \quad (5)$$

where $\langle v_{ij} \rangle$ is the value of the matrix element of the hyperfine interaction. This formula immediately gives the seccessful relations between meson and baryon masses[9-11]

$$M_\Lambda - M_N = 177 \text{ MeV} = (m_s - m_u)_B$$
$$= (m_s - m_u)_M = (3/4)(M_{K*} - M_\rho) + (1/4)(M_K - M_\pi) = 180 \text{ MeV} \quad (6a)$$

$$\frac{M_{K*} - M_K}{M_\rho - M_\pi} + \frac{3}{2}\,\frac{M_\Sigma - M_\Lambda}{M_\Delta - M_N} = 0.62 + 0.39 = 1.01 =$$

$$= \left(\frac{f_{uu}}{f_{su}}\right)_M + \left(1 - \frac{f_{uu}}{f_{su}}\right)_B = 1\,, \quad (6b)$$

where the subscripts M and B on functions of quark masses and hyperfine coefficients indicate that these are obtained from meson and baryon masses respectively. The relation (4a) used in the prediction (3a) is obtained from (6a). The relation (4b) used in the prediction (3b) is obtained from (6b) and the additional assumption[4] based on one-gluon exchange in QCD that $f_{ij} = m_i m_j$.

In their 1966 paper[9] Sakharov and Zel'dovich point out that the successful relation (6b) differs by a factor 3/2 from an SU(6) relation we had obtained[12] which disagrees with experiment. We had attempted to generalize to SU(6) the symmetry approach to hadron masses which had proved so successful in SU(3) with the Gell-Mann Okubo mass formula. We assumed that the symmetry breaking in the mass spectrum transformed in a very definite way under SU(6) and found disagreement with the observed masses. The SU(6) symmetry breaking operators required to fit meson and baryon masses were different. Assuming a common symmetry breaking gave the relation (6b) without the factor 3/2. The mass formula (5) explains why SU(3) symmetry gives good mass formulas and SU(6) fails. The flavor dependent terms transform under SU(3) like the isoscalar member of an octet to a very good approximation. But their SU(6) transformation properties are complicated and are different for mesons and baryons.

In 1965 the underlying physics behind the successful SU(6) classification of hadrons was very unclear. The symmetry approach was widely used, with attempts to embed SU(6) in some larger group including both space-time and internal symmetries. These failed because the underlying basis for the SU(6) classification was not a higher symmetry but the composite nature of the hadrons, as Sakharov and Zel'dovich already realized in 1966. Today we have the same problem at the quark-lepton level. It would be very useful today to find crucial clues in the experimental data that would distinguish between the group theoretical and composite models, like the factor 3/2 found by Sakharov and Zel'dovich in 1966.

We now examine the magnetic moments of quarks and leptons. Is g-2 a good test for composite models? Gluck[13] and Lipkin[14] say yes. Shaw, Silverman and Slansky,[15] and Brodsky and Drell[16] say no. They argue that any model that solves the "binding problem" also gives the right value for g-2.

But what is the "binding problem" and how do you know that you have solved it in a given model? Maybe it's easier to test the model by calculating g-2 than to verify that the "binding problem" has been solved.[17]

The nature of the difficulties involved in obtaining q-2 in a composite model is most strikingly illustrated in the following simple but extreme example. Consider an electron model as a composite of a neutral fermion and a scalar boson with charge -e. The naive nonrelativistic model for such a state has zero magnetic moment since the charged constituent has no angular momentum and the constituent with spin has no charge. A Dirac moment is obtained only if the charged boson has just the right peculiar value of orbital angular momentum to contribute the exact value of the moment for the combined system.

The argument of Refs. 15,16 suggest that this miracle occurs automatically if a light bound state can be constructed from a heavy scalar boson and a heavy fermion.

The essential peculiar feature of the bound state is that the scale defined by its size (or the masses of the constituents) is much smaller than the scale defined by its Compton wave length (or the mass of the bound state). They show that the anomalous magnetic moment and the excitation spectrum are determined by the scale of the size of the system, whereas the Dirac moment is determined by the mass or Compton wave length.

One very remarkable feature of this argument is its complete independence of the precise coupling of the individual constituents to the electromagnetic field; e.g. their electric charges. Thus the magnetic moment of such a low mass bound state must be very close to the Dirac moment <u>regardless of the electric charges of the constituents.</u> If the argument holds for a neutral fermion and a charged boson, it must also hold, <u>with the same wave function for the composite system,</u> for a charged fermion and a neutral boson, or for a fermion with charge xe and a boson with charge -(1 + x)e, where x can have any arbitrary value. This puts extreme conditions on the model, and suggests that any composite model made from two different elementary fields cannot have a simple description in terms of constituents, like the constituent quark model for hadrons.

This argument also shows that simple relativistic models with the Dirac equation in external potentials cannot describe such superstrong binding. Although such calculations show that a bound fermion in an external potential contributes a magnetic moment corresponding to its charge and mass,[18-20] the result is misleading, since the infinitely heavy potential source is assumed to have no charge and no spin. If all the charge of the system is on the infinitely heavy source and the fermion has no charge, the magnetic moment according to this calculation is zero. If the source has no charge, but is an infinitely heavy spin one boson, the total angular momentum of the system will be in the opposite direction to the angular momentum carried by the fermion, and the magnetic moment calculated in this way will have the wrong sign compared to the Dirac moment for the composite system.

The basic nature of the problem is clarified by examining the excitation spectrum for the electron. The lowest excited states with the same quantum numbers as the electron have a single electron and several electron-positron pairs. Simple relativistic models based on the Dirac or Bethe-Salpeter equations cannot be expected to describe an excitation spectrum which contains only multiparticle excitations up to a very high energy. Any model which attempts to describe the electron from first principles as a bound state of several super-strongly interacting particles must also give a reasonable description of multielectron systems. Thus any scattering amplitude in which the electron appears as a pole must have branch points at masses of $(2n+1)m_e$ beginning with $3m_e$.

The treatments of Refs. 15,16,18 do not consider these branch points and assume that above the electron pole the dominant contribution to photon-electron scattering in lowest order in α comes from states at very high mass. This effectively assumes that narrow bound states exist at a mass many orders of magnitude above the masses of millions of open decay channels allowed by all known conservation laws. Some drastically new type of conservation law or decoupling mechanism is needed to prevent the coupling and mixing of such high mass states with multiparticle states of an electron and a number of charge-conjugate electron positron pairs with vacuum quantum numbers. Such mixing would introduce unwanted low-mass contributions into the dispersion relations and sum rules which obtain an anomalous moment having a mass scale determined by the masses of the intermediate states coupled to an electron and a photon.

The neglect of all the contributions of all multielectron states in these treatments assumes that the superstrong "gluons" which bind the constituents into a single electron are somehow forbidden to be emitted by an electron and to create electron-positron pairs. In S-matrix language this means discarding millions of known nearby singularities in the scattering amplitude and using an amplitude with an entirely different analytic structure.

The essential features of this argument are illuminated by comparison with the analogous process of photon hadron scattering in the quark-parton model described by QCD.

Diagrams like those of Fig. 4 give the dominant contribution to deep inelastic photon-hadron scattering. The photon is absorbed by a quark-parton which cannot escape from the hadron because of confinement. Instead it creates additional parton-antiparton pairs by the emission and absorption of gluons and produces a multihadron final state. But the analogous diagram in photon scattering by a composite lepton must be negligible because it leads to the unobserved process of multilepton production by pair creation of constituent partons via superstrong gluons after one parton has absorbed the photon. The superstrong gluons which bind rishons into leptons must behave very differently from the colored gluons of QCD and cannot be allowed to be emitted by partons and subsequently create parton-antiparton pairs.

Another aspect of the electron mass spectrum to be faced by composite models is the absence of a low-lying excitation with spin 3/2 which can be excited by a photon on the electron, like the Δ is excited from the nucleon. Such a spin 3/2 state is expected to arise in many models. Some way must be found to get rid of it or to push it up to a very high mass if the model is to describe the leptons of the real world. In simple constituent models where the electron spin of 1/2 is obtained by coupling several non-trivial constituent spins to a total spin of 1/2, the spin 3/2 state arises from recoupling the constituent spins. In more general field theoretical models the same problem arises even though there may not be well defined constituents.

If such a spin 3/2 state exists in a given model, the sum rule arguments break down and the anomalous moment is not small. This is clear in the case of the nucleon. The N-Δ transition for example gives a large contribution to any sum rule for the anomalous moment of the nucleon. In a particular model it may be easier to calculate the ground state magnetic moment than to prove the absence of a low-lying spin 3/2 state. Estimates or bounds on the magnetic moment might be obtainable from models with approximate ground state wave functions. But if the excitation spectrum is exceedingly difficult to calculate, particularly for higher spin states, the masses of the lowest spin 3/2 excitations may be unknown and the argument of Refs. 15,16 completely useless.

This discussion of the electron spectrum can be summarized as requiring any composite model describing the electron to be "superrelativistic" with "superconfined" constituents.

Super-relativistic goes beyond both nonrelativistic and simple relativistic models. A non-relativistic composite model is characterized by constituent velocities $v \ll c$. Relativistic potential models using Dirac or Bethe-Salpeter equations are useful when velocities are no longer small, but when an excitation spectrum exists with energies smaller than the energy required to produce many bound state pairs. The composite model needed to describe the electron can be called superrelativistic because it must have a rich low-lying spectrum of multiparticle states. Models where it is much easier to create many pairs than to excite the original constituents to a radial or orbital excitation cannot be described in any simple way by potential models.

Superconfinement goes beyond the ordinary confinement of QCD. Quarks in QCD are not observable as free particles, but are observable as hadrons jets produced in collisions, are emitted in pairs in hadron decays by interactions arising from QCD gluons, and give rise to forces and scattering between hadrons resulting from quark or gluon exchange. If leptons are composites of constituents bound by some superstrong gauge field, these constituents are confined much more than in the sense of QCD. There must not be any observable effects in lepton-lepton and lepton-photon scattering which reveal the existence of additional interactions beyond QED. There can be no lepton jets produced by deep inelastic photon absorption on a charged constituent of the electron as in Fig. 4, and no observable electron-electron interactions resulting from superstrong gluon or constituent exchange. The superstrong interactions which bind the constituents of the electron must not only confine the constituents from being observed as free particles. They must also confine all the low energy secondary effects of these superstrong interactions normally observed in QCD. Note that even though QCD hadron physics has a characteristic scale of 1 GeV, effects of strong interactions due to QCD are seen at very low energies in the scattering of thermal neutrons.

One possible decoupling mechanism which could lead to super confinement of superstrong gluons is the large N limit whose features were first pointed out in a simplified model[21] by the author in 1968. With N colors and a one-gluon-exchange Yukawa potential, the effective interaction V_{eff} is proportional to Ng^2 for a color singlet state, but only to g^2 for a color uncorrelated pair. In the limit $N \to \infty$, $g^2 \to 0$, but with $V_{eff} \propto Ng^2$ fixed, the binding energy of the color singlet state remains constant, but there are no interactions between bound color-singlet states. There is a complete decoupling of the superstrong interaction. It is superstrong only inside color singlet particles and does not leak out.

Such a superrelativistic superconfined system will naturally have the Dirac magnetic moment to a very good approximation. The Dirac moment is obtained from the electromagnetic current density due to the motion of the entire bound system. The electromagnetic current for a non-relativistic moving bound system can be split into two components, one due to its center-of-mass motion and the other due to its internal degrees of freedom. In non-relativistic physics the center-of-mass motion is eliminated by going to the center-of-mass system. In relativistic quantum mechanics this is no longer possible. The magnetic moment of a Dirac electron which has no internal structure comes from the operators describing its motion as a whole.

The electron might have a composite structure on a very small scale which would not affect its motion required by relativistic quantum mechanics within a range of its Compton wave length. This fits into the picture of Refs. 15-16 in which the Dirac moment is always present and the anomalous moment comes from the structure. However, it is not obvious that the internal motions of a composite electron are separable and completely decoupled from the motions giving rise to the Dirac moment. This is again equivalent to requiring a complete decoupling of the low-lying multiparticle excitations. If all effects of the composite structure are superconfined, the anomalous moment must be very small with a mass scale determined by the excitation energy of the composite structure. But superconfinement will undoubtedly be harder to tests and prove in any proposed model than confinement in QCD. Thus magnetic moment calculations may prove to be highly significant test of such models.

FOOTNOTES AND REFERENCES

†On leave from Department of Physics, Weizmann Institute of Science, Rehovot, Israel.

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FIGURE CAPTIONS

Fig. 1 The Rishon Cube.

Fig. 2 The Han-Nambu Cube.

Fig. 3 A Card From Andrei Sakharov in Gor'kii.

Fig. 4 Deep Inelastic Photon Scattering in a Parton Model.

ANL-P-15,951

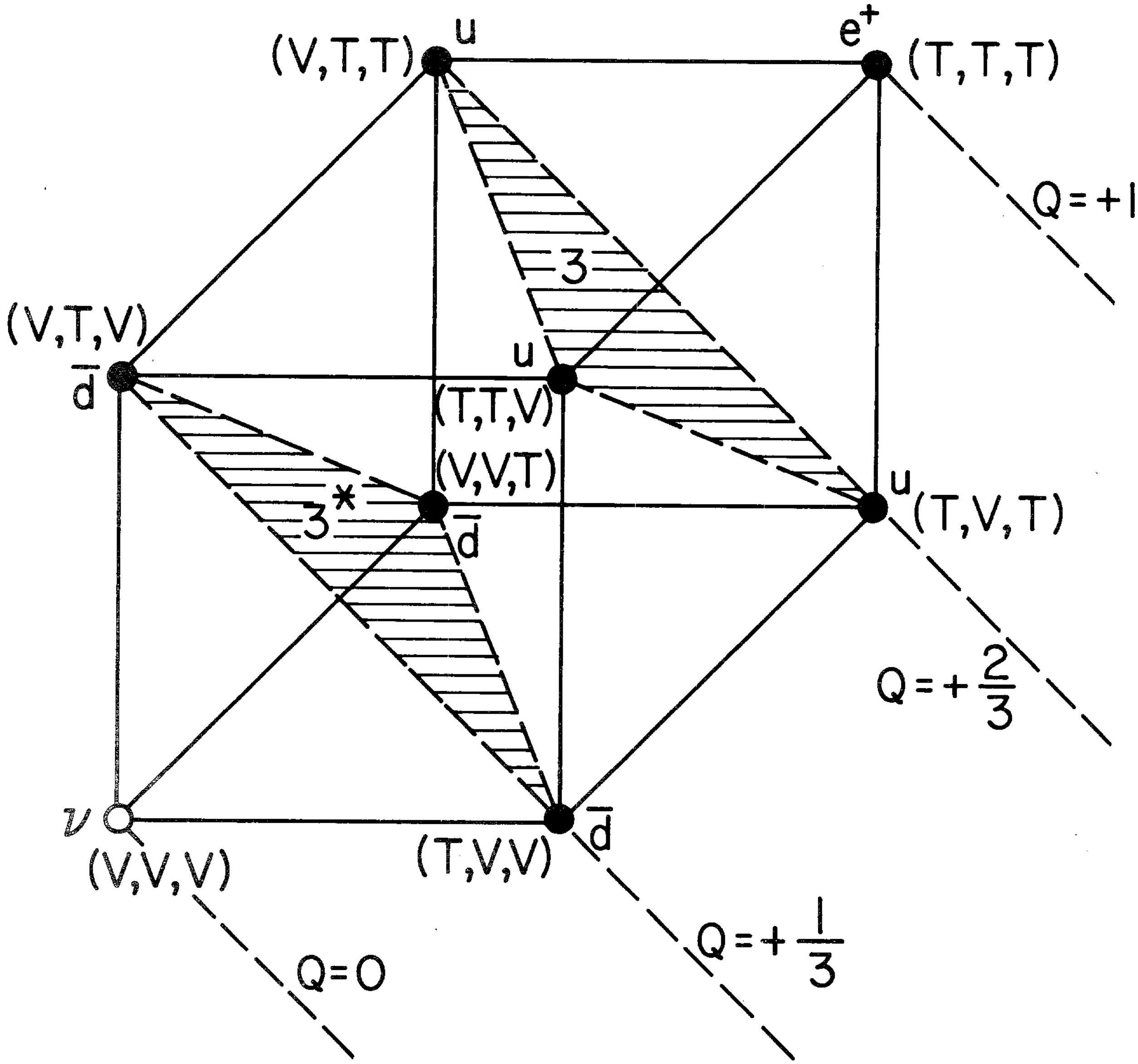

Fig. 1

ANL-P-15,950

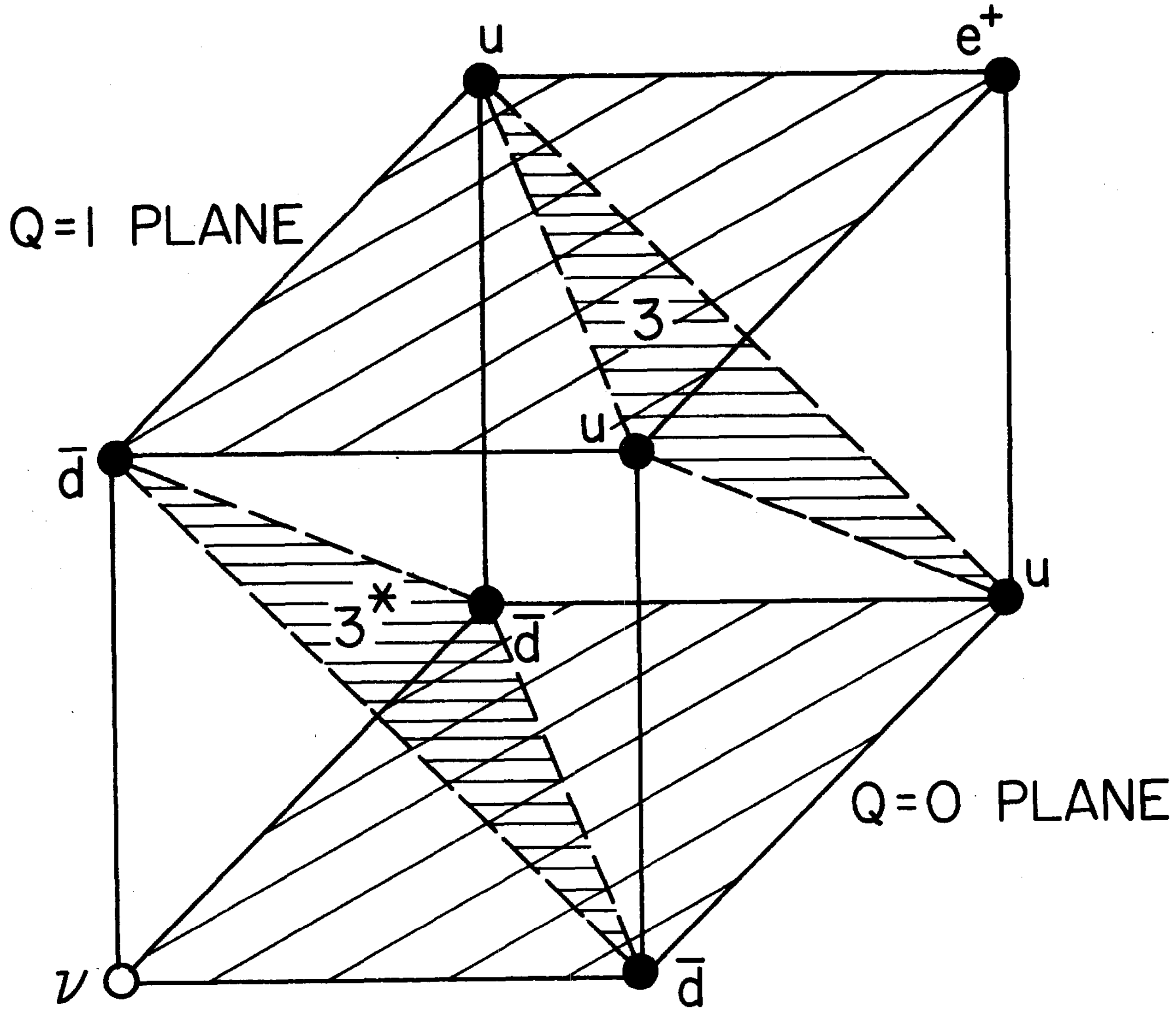

Fig. 2

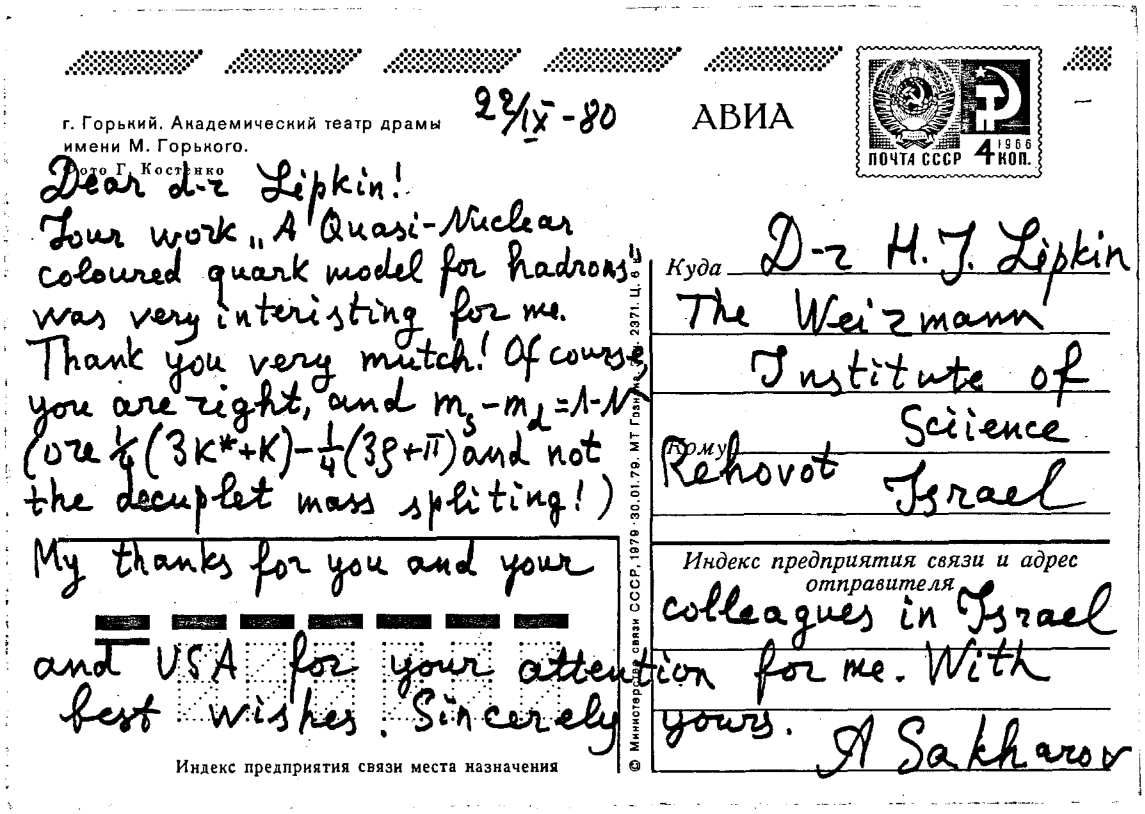

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Фото Г. Костенко

22/IX-80

АВИА

ПОЧТА СССР 4 КОП. 1966

Dear d-r Lipkin!
Your work „A Quasi-Nuclear coloured quark model for hadrons" was very interisting for me. Thank you very mutch! Of course, you are right, and $m_s - m_d = \Lambda - N$ (or $\frac{1}{4}(3K^* + K) - \frac{1}{4}(3\rho + \pi)$ and not the decuplet mass spliting!)
My thanks for you and your colleagues in Israel and USA for your attention for me. With best wishes. Sincerely yours. A Sakharov

Куда D-r H. J. Lipkin
The Weizmann Institute of Science

Кому Rehovot Israel

Индекс предприятия связи и адрес отправителя

Индекс предприятия связи места назначения

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Fig. 3

ANL-P-16,116

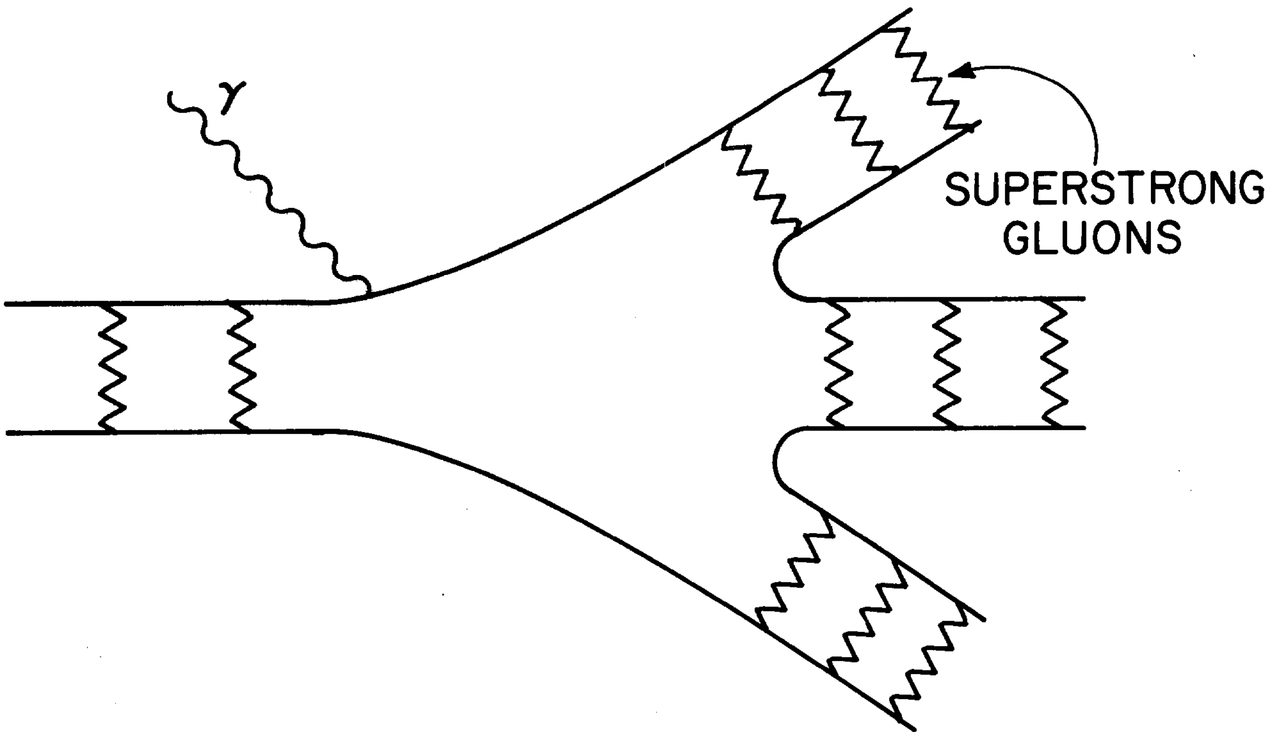

Fig. 4